GEOMETRIC TRACK AND TRACK/VEHICLE ANALYZERS AND METHODS FOR CONTROLLING RAILROAD SYSTEMS

This is a continuation-in-part application of co-pending Patent Application Ser. No. 10/073,831, filed February 11, 2002 which was a continuation-in-part application of Patent Application Ser. No. 09/594,286 (now U.S. Pat. No. 6,347,265), filed on June 15, 2000 and claiming the benefit of U.S. Provisional Patent Application Ser. Nos. 60/139,217, filed June 15, 1999, and 60/149,333, filed on August 17, 1999. The disclosures of each of these utility and provisional patent applications are incorporated herein by reference.

Background of the Invention

[0001] The invention relates to determining, recording, and processing the geometry of a railroad track, determining, recording, and processing the geometry of a vehicle traveling on the track, and using such information to control operation of one or more vehicles on the track and to effectuate maintenance of the track. It finds particular application in conjunction with using the geometric information to improve operational safety and overall efficiency (e.g., fuel efficiency, vehicle wheel wear, and track wear) and will be described with particular reference thereto. It will be appreciated, however, that the invention is also amendable to other like applications.

[0002] Heretofore, track geometry systems determine and record geometric parameters of railroad tracks used by vehicles (e.g., railroad cars and locomotives) and generate an inspection or work notice for a section of track if the parameters are outside a predetermined range. Each vehicle includes a body secured to a truck, which rides on the track. Conventional systems use a combination of inertial and contact sensors to indirectly measure and quantify the geometry of the track. More specifically, an inertial system mounted on the truck senses motion of the truck in relation to the track. A plurality of transducers measure relative motion of the truck in relation to the track.

[0003] One drawback of conventional systems is that a significant number of errors occur from transducer failures. Furthermore, significant errors also result from a lack of direct measurements of the required quantities in a real-time manner.

[0004] Furthermore, conventional inertial systems typically use off-the-shelf gyroscopes and other components, which are designed for military and aviation applications. Such off-the-shelf components are designed for high rates of inertial change found in military and aircraft applications. Therefore, components used in conventional systems are poorly suited for the relatively low amplitude and slow varying signals seen in railroad applications. Consequently, conventional systems compromise accuracy in railroad applications.

[0005] The current technology in locomotive traction control is based on an average North American curve of approximately 2.5 degrees. If real-time rail geometry data, including current curvature and superelevation and cross-level, can be provided, then the drive system can be optimized for current track conditions, resulting in maximum efficiency.

[0006] The relationship between the tractive force that drives the locomotive, or other type of vehicle, forward on a rail is expressed by the following equation:

$$F_{Traction} = F_{Normal} * u$$

where u is the coefficient of static friction and F_{Normal} is the normal force at the rail / wheel interface.

[0007] Balance speed is the optimum speed of the vehicle at which the resultant force vector is normal to the rail. By maintaining a vehicle at its balanced speed point, F_{Normal} is maximized. Accordingly, $F_{Traction}$ is also maximized when the vehicle is operated at its balanced speed. Furthermore, by maintaining the drive wheels at the highest point of static friction while operating at the balanced speed, the maximum amount of available tractive force ($F_{Traction}$) is achieved.

[0008] A small change in the velocity (V) through a curve results in significant changes in the lateral (centripetal) forces, as shown in the following equation:

$$F_{Lateral} = Mass * A_{lateral},$$

where $A_{lateral} = (1/ R_{curve}) \cdot V\text{^} 2$

[0009] No current system provides the information necessary to compute the balance speed and therefore determine the most efficient operation of the train. Additionally, no current device or system allows for the inspection of rail track structures, determination of track geometric conditions, and identification of track defects in real-time. Furthermore, no current device or system communicates such

information to other locomotive control mechanisms (e.g., locomotive control computers) in real-time allowing for real-time locomotive control.

Summary of the Invention

[0010] The invention provides a new and improved apparatus and method, which overcomes the above-referenced problems and others. The invention acquires and analyzes rail geometry information in real-time to provide drive control systems of trains and autonomous vehicles with information so locomotive control circuits can reduce flanging forces at the wheel / rail interface, thereby increasing the locomotive tractive force on a given piece of track. The net result is increased fuel efficiency, reduced vehicle wheel wear, and reduced rail wear. The geometry information can also be used to control selective onboard wheel lubrication systems. The addition of the selected lubrication system further helps to reduce wheel/rail wear. This optimizes the amount of tonnage hauled per unit cost for fuel, rail maintenance, and wheel maintenance.

[0011] Through inter-train communication, relevant track defect and traction control information can be communicated to lead units and helper units (i.e., locomotives) in the train. This permits the lead units and helper units to adjust control strategies to improve operational safety and optimize overall efficiency of the train.

[0012] Where the rail geometry information is collected and analysed in real-time against track standards, the results of the analysis are communicated to a display device (for use by the engineer), locomotive control computers, and a centralized control office as corrective measures, optizimized control strategies, and recommended courses of action. The locomotive control computers respond to such communications by taking appropriate actions to reduce risks of derailment and other potential hazards, as well as improving the overall efficiency of the train. The remote communications to the centralized control office also provide coordinated dispatch of personnel to perform maintenance for defects detected by the system, as well as a centralized archive of defect data for historical comparison.

[0013] In one embodiment, a track analyzer included on a vehicle traveling on a track is provided. The track analyzer includes: a track detector for determining track parameters comprising at least one parameter of a group including a grade of the

track, a superelevation of the track, a gauge of the track, and a curvature of the track and a computing device, communicating with the track detector, for determining in real-time if the track parameters are within acceptable tolerances, and, if any one of the track parameters are not within acceptable tolerances, generating corrective measures.

[0014] In another embodiment, a method for analyzing a track on which a vehicle is traveling is provided. The method includes: a) determining track parameters comprising at least one parameter of a group including a grade of the track, a superelevation of the track, a gauge of the track, and a curvature of the track, b) determining in real-time if the track parameters are within acceptable tolerances, and c) if any one of the track parameters are not within acceptable tolerances, generating corrective measures.

[0015] In yet another embodiment, a track/vehicle analyzer included on a vehicle traveling on a track is provided. The track/vehicle analyzer includes: a track detector for determining track parameters comprising at least one parameter of a group including a grade of the track, a superelevation of the track, a gauge of the track, and a curvature of the track, a vehicle detector for determining vehicle parameters comprising at least one parameter of a group including a speed of the vehicle relative to the track, a distance the vehicle has traveled on the track, forces on a drawbar of the vehicle, a set of global positioning system coordinates for the vehicle, and a set of orthogonal accelerations experienced by the vehicle, and a computing device, communicating with the track detector and the vehicle detector, for determining in real-time if the track parameters and the vehicle parameters are within acceptable tolerances and, if any one of the track parameters or the vehicle parameters are not within acceptable tolerances, generating corrective measures.

[0016] In still another embodiment, a method of analyzing a vehicle and a track on which the vehicle is traveling is provided. The method includes: a) determining track parameters comprising at least one parameter of a group including a grade of the track, a superelevation of the track, a gauge of the track, and a curvature of the track, b) determining vehicle parameters comprising at least one parameter of a group including a speed of the vehicle relative to the track, a distance the vehicle has traveled on the track, forces on a drawbar of the vehicle, a set of global positioning

system coordinates for the vehicle, and a set of orthogonal accelerations experienced by the vehicle, c) determining in real-time if the track parameters and the vehicle parameters are within acceptable tolerances, and d) if any one of the track parameters or the vehicle parameters are not within acceptable tolerances, generating corrective measures.

[0017] In yet another embodiment, a track/vehicle analyzer included on a vehicle traveling on a track is provided. The track/vehicle analyzer includes: a track detector for determining track parameters comprising at least one parameter of a group including a grade of the track, a superelevation of the track, a gauge of the track, and a curvature of the track, a vehicle detector for determining vehicle parameters comprising at least one parameter of a group including a speed of the vehicle relative to the track, a distance the vehicle has traveled on the track, forces on a drawbar of the vehicle, a set of global positioning system coordinates for the vehicle, and a set of orthogonal accelerations experienced by the vehicle, a computing device, communicating with the track detector and vehicle detector, for a) determining a plurality of calculated parameters as a function of the track parameters and the vehicle parameters, b) determining in real-time if the track parameters, the vehicle parameters, and the calculated parameters are within acceptable tolerances, and c) if any one of the track parameters, the vehicle parameters, or the calculated parameters are not within acceptable tolerances, generating corrective measures, and a communications device in communication with the computing device for communicating the corrective measures to at least one of a truck lubrication system and a truck steering mechanism in at least one of the vehicle, a locomotive associated with the vehicle, or a railroad car associated with the vehicle.

[0018] In still another embodiment, a method for improving operational safety and overall efficiency, including fuel efficiency, vehicle wheel wear, and track wear, for a track and a vehicle traveling on the track is provided. The method includes: a) determining track parameters comprising at least one parameter of a group including a grade of the track, a superelevation of the track, a gauge of the track, and a curvature of the track, b) determining vehicle parameters comprising at least one parameter of a group including a speed of the vehicle relative to the track, a distance the vehicle has traveled on the track, forces on a drawbar of the vehicle, a set of global positioning

system coordinates for the vehicle, and a set of orthogonal accelerations experienced by the vehicle, c) determining a plurality of calculated parameters as a function of the track parameters and the vehicle parameters, including a balance speed parameter for the vehicle, d) determining in real-time if the track parameters, the vehicle parameters, and the calculated parameters associated with the balance speed parameter are within acceptable tolerances associated with the balance speed parameter, e) if any one of the track parameters, the vehicle parameters, or the calculated parameters associated with the balance speed parameter are not within acceptable tolerances, determining a first optimized lubrication strategy for the vehicle, and f) communicating the first optimized lubrication strategy to at least one truck lubrication system in the vehicle to promote operational safety and overall efficiency, including fuel efficiency, minimizing vehicle wheel wear, and minimizing track wear.

[0019] In yet another embodiment, a method for improving operational safety and overall efficiency, including fuel efficiency, vehicle wheel wear, and track wear, for a track and a vehicle traveling on the track is provided. The method includes: a) determining track parameters comprising at least one parameter of a group including a grade of the track, a superelevation of the track, a gauge of the track, and a curvature of the track, b) determining vehicle parameters comprising at least one parameter of a group including a speed of the vehicle relative to the track, a distance the vehicle has traveled on the track, forces on a drawbar of the vehicle, a set of global positioning system coordinates for the vehicle, and a set of orthogonal accelerations experienced by the vehicle, c) determining a plurality of calculated parameters as a function of the track parameters and the vehicle parameters, including a balance speed parameter for the vehicle, d) determining in real-time if the track parameters, the vehicle parameters, and the calculated parameters associated with the balance speed parameter are within acceptable tolerances associated with the balance speed parameter, e) if any one of the track parameters, the vehicle parameters, or the calculated parameters associated with the balance speed parameter are not within acceptable tolerances, determining a first optimized steering strategy for the vehicle, and f) communicating the first optimized steering strategy to at least one truck steering mechanism in the vehicle to promote operational safety and overall

efficiency, including fuel efficiency, minimizing vehicle wheel wear, and minimizing track wear.

[0020] In still another embodiment, a method for improving operational safety and overall efficiency, including fuel efficiency, vehicle wheel wear, and track wear, for a track and a train traveling on the track is provided. The method includes: a) determining track parameters comprising at least one parameter of a group including a grade of the track, a superelevation of the track, a gauge of the track, and a curvature of the track, b) determining train parameters associated with a vehicle of the train including forces on a drawbar of the vehicle, c) determining a plurality of calculated parameters as a function of the track parameters and the train parameters, d) determining in real-time if the track parameters, the train parameters, and the calculated parameters are within acceptable tolerances, e) if any one of the track parameters, the train parameters, or the calculated parameters are not within acceptable tolerances, generating corrective measures, and f) communicating the corrective measures to at least one of a truck lubrication system and a truck steering mechanism in at least one vehicle associated with the train to promote operational safety and overall efficiency, including fuel efficiency, minimizing vehicle wheel wear, and minimizing track wear.

[0021] Benefits and advantages of the invention will become apparent to those of ordinary skill in the art upon reading and understanding the description of the invention provided herein.

Brief Description of the Drawings

[0022] The invention is described in more detail in conjunction with a set of accompanying drawings.

[0023] FIGURE 1 illustrates a vehicle on a track.

[0024] FIGURE 2 illustrates a mechanical vertical gyroscope of an embodiment of the invention.

[0025] FIGURE 3 is a block diagram of a mechanical vertical gyroscope sensor circuit.

[0026] FIGURE 4 illustrates a mechanical rate gyroscope of an embodiment of the invention.

[0027] FIGURE 5 illustrates a vehicle traveling on a section of curved track.

[0028] FIGURE 6 illustrates a speed assembly of an embodiment of the invention.

[0029] FIGURE 7 illustrates a gear and speed sensor of the speed assembly of FIGURE 6.

[0030] FIGURE 8 is a block diagram of a speed sensor circuit.

[0031] FIGURE 9 illustrates a distance measurement assembly of an embodiment of the invention.

[0032] FIGURE 10 is a timing diagram for determining direction traveled on a track using the distance measurement assembly of FIGURE 9.

[0033] FIGURE 11 illustrates the definition of "degree of curve."

[0034] FIGURE 12 is a graph of "degree of curvature" versus distance.

[0035] FIGURE 13 illustrates a cross-level (i.e., superelevation) measurement and an example definition of gauge measurement for a track.

[0036] FIGURE 14 is a block diagram of a track analyzer in an embodiment of the invention.

[0037] FIGURE 15 is a block diagram of a computer system of an embodiment of the invention.

[0038] FIGURE 16 illustrates a location of an inertial navigation unit of an embodiment of the invention.

[0039] FIGURE 17 illustrates a non-contact gauge measurement assembly of an embodiment of the invention.

[0040] FIGURE 18 illustrates an accelerometer assembly of an embodiment of the invention.

[0041] FIGURE 19 illustrates a location of a drawbar force assembly of an embodiment of the invention.

[0042] FIGURE 20 illustrates the drawbar force assembly of an embodiment of the invention.

[0043] FIGURE 21 is a block diagram of a track/vehicle analyzer in an embodiment of the invention.

[0044] FIGURE 22 is an information flow diagram for an embodiment of a track/vehicle analyzer.

Detailed Description of the Preferred Embodiments

[0045] While the invention is described in conjunction with the accompanying drawings, the drawings are for purposes of illustrating exemplary embodiments of the invention and are not to be construed as limiting the invention to such embodiments. It is understood that the invention may take form in various components and arrangement of components and in various steps and arrangement of steps beyond those provided in the drawings and associated description. Within the drawings, like reference numerals denote like elements.

[0046] With reference to FIGURE 1, a track **10** may be defined by a longitudinal axis **12**, a roll axis **13**, a lateral axis **14**, a pitch axis **15**, a vertical axis **16**, and a yaw axis **17**. The roll axis measures roll (i.e., cross elevation, cross-level, or superelevation) of the track about the longitudinal axis. The pitch axis measures pitch (i.e., grade) of the track about the lateral axis. The yaw axis measures yaw (i.e., rate of curvature) of the track about the vertical axis. As shown in FIGURE 1, the longitudinal axis **12**, roll axis **13**, lateral axis **14**, pitch axis **15**, vertical axis **16**, and yaw axis **17**also relate to a vehicle **28** traveling on the track **10**. The vehicle **28** may be an autonomous vehicle (e.g., a self-propelled railroad car or a track inspection truck) or associated with multiple vehicles in a train. Where the vehicle **28** is in a train, it may be any vehicle of the train, including locomotives or railroad cars making up the train.

[0047] With reference to FIGURE 14, one embodiment of the invention is a track analyzer **140**. The track analyzer is included on a vehicle **28** traveling on a track **10**. The track analyzer **140** includes a vertical gyro assembly **20, 202**, a rate gyro assembly **50, 204**, a non-contact gauge measurement assembly **206**, an accelerometer assembly **208**, a temperature sensing assembly **210**, a keyboard **212**, a mouse **214**, a video display device **142**, a communications device **216**, and a computer system **218**.

[0048] With reference to FIGURE 21, another embodiment of the invention is a track/vehicle analyzer **200**. The track/vehicle analyzer is also included on a vehicle **28** traveling on a track **10**. The track/vehicle analyzer **200** includes a vertical gyro assembly **20, 202**, a rate gyro assembly **50, 204**, a gauge measurement assembly **206**, a speed assembly **70**, a distance measurement assembly **91**, a drawbar force assembly **220**, a global positioning system **222**, an accelerometer assembly **208**, a temperature

sensing assembly **210**, a keyboard **212**, a mouse **214**, a video display device **142**, a communications device **216**, and a computer system **218**. The communication device **216** may communicate with various external components associated with the vehicle, other vehicles of a train associated with the vehicle, and overall control of vehicles and trains on the track. For example, as shown in FIGURE 21, the communication device **216** may communicate with one or more locomotive control computers (traction unit(s)) **250**, one or more locomotive control computers (helper unit(s)) **254**, a centralized control office **260**, one or more track features **272**, a truck lubrication system **274**, and a truck steering mechanism **276**.

[0049] The truck lubrication system **274** applies a suitable lubricant to trucks, wheels, and other components associated with the trucks that require periodic lubrication. Each vehicle may include a truck lubrication system **274** that services the trucks and corresponding wheels associated with that vehicle. Alternatively, the truck lubrication system may service trucks and corresponding wheels on a plurality of vehicles. Conversely, independent truck lubrication systems may be provided for each truck and corresponding wheels on each vehicle. Of course, any combination of these options may be implemented in a given vehicle and/or a given train. In any truck lubrication system implementation, the track/vehicle analyzer **200**, via the communication device **216**, may command one or more truck lubrication systems **274** to apply lubricant to one or more wheels based on certain conditions detected by the track/vehicle analyzer. The truck lubrication system may include any type of lubrication system capable of delivering sufficient quantities of suitable lubricant in response to control signals communicated from another device, such as the computer system 218 of the track/vehicle analyzer 200.

[0050] The truck steering mechanism **276** can turn one or more trucks associated with a given vehicle left or right in order to follow curves in the track. Each vehicle may include a truck steering mechanism **276** that steers the trucks associated with that vehicle. Alternatively, independent truck steering mechanisms may be provided for each truck on each vehicle. Of course, any combination of these options may be implemented in a given vehicle and/or a given train. In any truck steering mechanism implementation, the track/vehicle analyzer **200**, via the communication device **216**, may command one or more truck steering mechanisms **276** to the corresponding

truck(s) based on certain conditions detected by the track/vehicle analyzer (e.g., movement of the corresponding vehicle through a curved section of track). The truck steering mechanism may use any type of control mechanism (e.g., hydraulic, servo, pneumatic, etc.-controlled cylinders and associated linkage components) capable of turning the truck left or right in response to control signals communicated from another device, such as the computer system 218 of the track/vehicle analyzer 200.

[0051] With reference to FIGURE 22, an information flow diagram for an embodiment of the track/vehicle analyzer **200** is provided. As shown, the track/vehicle analyzer includes a video display device **142**, a communications device **216**, a global positioning system **222**, sensors **262**, a track feature detection process **264**, a geometry system process **266**, a vehicle optimization process **268**, and a derailment modeler process **270**. A locomotive control computer **250**, **254**, a centralized control office **260**, a track feature **272**, a truck lubrication system **274**, and a truck steering mechanism **276** are external components that communicate with the analyzer via the communications device **216**. The locomotive control computer **250**, **254**, truck lubrication system **274**, and truck steering mechanism **276** are associated with the vehicle **28** wherein the track/vehicle analyzer is disposed. Where the vehicle **28** is one of multiple vehicles in a train, each vehicle of the train may include a truck lubrication system **274** and a truck steering mechanism **276**. Moreover, any vehicle may include multiple truck lubrication systems **274** and/or multiple truck steering mechanisms **276**, independently associated with each truck assembly on the vehicle or associated with any combination of truck assemblies. Therefore, communications between the track/vehicle analyzer and the locomotive control computer **250**, **254**, truck lubrication system **274**, and truck steering mechanism **276** are intra-train communications. The intra-train communications may implement any suitable wired or wireless technology in any combination. The centralized control office and track feature are not associated with the vehicle or a train associated with the vehicle. Therefore, communications between the track/vehicle analyzer and the centralized control office or the track feature are remote communications.

[0052] The global positioning system **222**, sensors **262**, locomotive control computer **250**, **254**, centralized control office **260**, and track feature **272** are the potential sources of raw information. The heart of the track/vehicle analyzer **200** is

the geometry system process **266**, which receives raw information from any of these sources. In addition, the track feature detection process **264** receives raw information from the global positioning system and communicates with the track feature via the communications device **216**. The track feature detection process provides processed information to the geometry system process. The geometry system process processes the raw information and processed track feature information to detect hazardous conditions associated with the track **10**. If hazardous conditions are detected, the geometry system process communicates corrective actions to a vehicle operator via the video display device **142** and to the locomotive control computer and the centralized control office via the communications device.

[0053] The geometry system process **266** also communicates with the vehicle optimizer process **268**. The vehicle optimizer process **268** processes raw and processed information in cooperation with the geometry system process to determine an optimized control strategy for the vehicle **28**. The optimized control strategy is communicated to the vehicle operator via the video display device **142** and to the locomotive control computer **250, 254** via the communications device **216**. Feedback is communicated from the locomotive control computer to the vehicle optimizer process, creating an automated closed-loop control mechanism.

[0054] The vehicle optimizer process **268** also processes the raw and processed information in cooperation with the geometry system process to determine an optimized lubrication strategy for truck assemblies in the vehicle **28** and, if the vehicle is associated in a train, truck assemblies in other vehicles associated with the train. The optimized lubrication strategy, for example, may take into account any combination of the geometric and track conditions, as well as the speed, distance, and force conditions, experienced by the vehicle(s). The optimized lubrication strategy is communicated to the vehicle operator via the video display device **142** and to the truck lubrication system **274** via the communications device **216**. Feedback may be communicated from the truck lubrication system to the vehicle optimizer process, creating an automated closed-loop control mechanism. Alternatively, the optimized lubrication strategy may be included in the optimized control strategy provided to the locomotive control computer **250, 254** and the locomotive control computer may control the truck lubrication system accordingly.

[0055] Similarly, the vehicle optimizer process **268** also processes the raw and processed information in cooperation with the geometry system process to determine an optimized steering strategy for truck assemblies in the vehicle **28** and, if the vehicle is associated in a train, truck assemblies in other vehicles associated with the train. The optimized steering strategy, for example, may take into account any combination of the geometric and track conditions, particularly track curvature, as well as the speed, distance, and force conditions, experienced by the vehicle(s). The optimized steering strategy is communicated to the vehicle operator via the video display device **142** and to the truck steering mechanism **276** via the communications device **216**. Feedback may be communicated from the truck steering mechanism to the vehicle optimizer process, creating an automated closed-loop control mechanism. Alternatively, the optimized steering strategy may be included in the optimized control strategy provided to the locomotive control computer **250, 254** and the locomotive control computer may control the truck steering mechanism accordingly.

[0056] The geometry system process **266** also communicates with the derailment modeler process **270**. The derailment modeler process processes raw and processed information in cooperation with the geometry system process to dynamically model each vehicle in a train associated with the vehicle **28** wherein the track/vehicle analyzer **200** is disposed to determine which vehicle has the highest statistical probability for causing a derailment. When a hazardous derailment condition exists, the derailment modeler process also determines a recommended course of action, including an optimized control strategy and, optionally, an optimized steering strategy. The recommended course of action is communicated to the vehicle operator via the video display device **142** and to the locomotive control computer **250, 254**, truck steering mechanism **276**, and centralized control office **260** via the communications device **216**.

[0057] With reference to FIGURE 15, the computer system **218** includes a power supply **36**, one or more analog to digital converters **38, 40, 90**, a frequency to voltage converter **88**, a buffer **224**, a look-up table **226**, and a computing device **42**. The power supply **36** provides a source of power to various detector assemblies (e.g., **20, 50**) of the analyzer **140, 200**. As shown in FIGURES 14 and 21, each detector assembly provides one or more raw signals to the computer system **218**. These raw

signals may be in analog, digital pulses, digital, or other forms and may require various types of signal conditioning and/or buffering in an input stage to the computing device **42**. For example, raw analog signals from the detector assemblies are transformed by an analog-to-digital converter **38**, **40**, **90** into a digital format. Similarly, raw digital pulse signals are conditioned by a frequency-to-voltage converter **88** and further conditioned by an analog-to-digital converter **90**. Raw digital signals from the detector assemblies are usually isolated by a buffer **224** and may be scaled prior to being received by the computing device. The computing device **42** and signal conditioning and buffering circuits provide channels for receiving each track parameter (i.e., grade, superelevation, rate of curvature, and gauge) and each vehicle parameter (i.e., speed, distance, drawbar force, global positioning system (GPS) coordinates, acceleration, and temperature) from the detector assemblies.

[0058] With reference to FIGURES 1 and 2, a vertical gyroscope **20** ("gyro") includes an inner gimbal **22**, which measures the pitch (i.e., grade) **14** and an outer gimbal **24**, which measures the roll (i.e.,, cross elevation, cross-level, or superelevation) **12**. Respective bearings **26** secure the inner and outer gimbals **22, 24**, respectively, to a vehicle (e.g., railroad car) **28** traveling on the track **10**. The vertical gyro **20** includes a spin motor **30**, which always remains substantially vertical. The spin motor **30** preferably spins at about 30,000 revolutions per minute ("rpm"). In this manner, the spin motor **30** acts as an inertial reference (e.g., axis). Any motion by the inner gimbal **22** and/or the outer gimbal **24** is measured against the inertial reference of the spin motor **30**.

[0059] Although a mechanical vertical gyroscope **20** is shown in FIGURE 2, it is to be understood that any device, which has a spinning mass with a spin axis that turns between two low-friction supports and maintains an angular orientation with respect to inertial coordinates when not subjected to external torques, is contemplated.

[0060] Furthermore, it is to be understood that non-mechanical gyroscopes are also contemplated. For example, a solid state vertical gyroscope **202** that can supply roll axis and pitch axis information and be corrected for outside influences (e.g., external influences of acceleration and temperature on the sensor elements), is contemplated. The solid state vertical gyroscope **202** includes a grade determiner for

determining the grade of the track and a superelevation determiner for determining the superelevation of the track and is sometimes referred to as an inertial measurement unit (IMU). The solid state vertical gyroscope (IMU) **202**, like the mechanical vertical gyroscope **20**, is mounted on the vehicle **28** for measuring roll **12** and pitch **14** (see FIGURE 15).

[0061] With reference to FIGURES 2 and 3, raw analog electric signals are generated by first and second potentiometers **32, 34**, respectively, which are preferably powered by a power supply **36** (e.g., a ±10 VDC power supply). The first and second potentiometers **32, 34** are secured to the outer and inner gimbals **24, 22**, respectively. The analog signals are transmitted to respective analog-to-digital converters **38, 40**. The analog-to-digital converters **38, 40** transform the analog signals into a digital format. The digital signals are then transmitted to the computing device **42**. In this manner first and second channels to the computing device represent the grade and cross-level (i.e., superelevation) of the track, respectively. Similarly, in regard to the rate gyro assembly **50, 204**, a third channel to the computing device represents the rate of curvature of the track.

[0062] When setting up the system, it is important that the roll axis **12** is substantially parallel to the track **10**. Then, by default the pitch axis **14** is substantially perpendicular to the longitudinal axis **12** of the track **10**.

[0063] With reference to FIGURE 4, a rate gyroscope **50** includes first and second springs **52, 54**, respectively. The springs **52, 54** give the rate gyro **50** a single degree of freedom around an axis of rotation located above a spin motor **58**. A torque axis **59** is in a direction perpendicular to a gimbal axis **61** around which the spin motor **58** turns. A measurement potentiometer **60** detects displacement of the spin motor **58** from a reference line parallel to the torque axis **59**. The rate gyroscope **50** is mounted on the vehicle **28** for measuring yaw **16** (see FIGURE 1).

[0064] More specifically, as long as the vehicle **28** is traveling straight, the forces on the springs **52, 54** are equal. Therefore, the torque axis remains parallel to the direction of travel. When the vehicle **28** travels through a curve, having a radius **R**, along the track **10** (see FIGURE 5), the spin motor **58** and torque axis **59** tend to remain in the same direction as when the vehicle **28** travels straight. In this manner, the rate gyro **50** measures a displacement from a reference line (e.g., a rate-of-change

of displacement about the yaw axis). The angle of rotation (displacement) about the gimbal axis **61** corresponds to a measure of the input angular rate (angular velocity).

[0065] Although a mechanical rate gyroscope is shown in FIGURE 4, it is to be understood that any device, which has a spinning mass with a spin axis that turns between two low-friction supports and maintains an angular orientation with respect to inertial coordinates when not subjected to external torques, is contemplated.

[0066] Furthermore, it is to be understood that non-mechanical rate gyroscopes are also contemplated. For example, a fiber optic gyroscope (FOG) **204** that can supply rate axis information is shown in the track/vehicle analyzer **200** of FIGURE 20. The fiber optic rate gyroscope (FOG) **204** is based on the Sagnac interferometer effect as is a laser ring gyroscope. FOGs are typically based on an optical fiber concept using elliptical-core polarization maintaining fiber, directional coupler(s), and a polarizer. Like in the embodiment with the mechanical rate gyroscope, the fiber optic rate gyroscope **204** is mounted on the vehicle **28** for measuring yaw **16** (see FIGURE 1).

[0067] With reference to FIGURES 13 and 17, the non-contact gauge measurement assembly **208** includes a laser-camera assembly **228** positioned over each rail **130** of the track **10**. The laser **230** "paints" a line perpendicular to the longitudinal axis of the rails **130**. The camera **232** captures the laser light image reflected from the head **234** of the rail for both rails. In the embodiment being described, images from the cameras are transmitted to the computing device **42** for processing. The camera images are processed such that the points 5/8 of an inch from the top **234** of rail (i.e., gauge point) are determined within the image frames. These images are further processed together to yield the distance between the rails **130** (i.e., the "gauge" **236** of the rail). FIGURE 13, for example, shows a railroad track where 56.5" is the standard distance between the rails. The laser can also direct a beam of light to the gauge point of each rail and, using triangulation techniques, compute the gauge distance

[0068] With reference to FIGURE 18, the accelerometer assembly **208** includes three accelerometers **238, 240, 242** that are mounted at right angles to each other to accurately determine accelerations along the longitudinal axis **12**, lateral axis **14**, and vertical axis **16** (see FIGURE 1). The X accelerometer **238** detects accelerations in

the longitudinal axis **12** and provides an A_X signal. The Y accelerometer **240** detects accelerations in the lateral axis **14** and provides an A_Y signal. The Z accelerometer **242** detects accelerations in the vertical axis **16** and provides an A_Z signal. Each accelerometer **238, 240, 242** produces a DC voltage proportional to the acceleration applied to the vehicle in the direction under study. The analog signals are transmitted to respective analog-to-digital converters (e.g., **38**), transformed into a digital format, then to the computing device **42** (see FIGURE 15).

[0069] With reference to FIGURES 14 and 21, the temperature sensing assembly 210 includes one or more temperature probes. One temperature probe is mounted with instruments in the IMU. Other temperature probes are mounted with other temperature sensitive detectors and instruments. Each temperature probe produces an analog signal output that is proportional to the temperature of its environment (e.g., the interior of IMU package). The analog signal is transmitted to an analog-to-digital converter (e.g., 38), which transforms the analog signal into a digital format, then to the computing device 42 (see FIGURE 15).

[0070] With reference to FIGURES 6, a speed assembly (e.g., a speedometer) **70** includes a toothed gear **72** and a pick-up (sensor) **74**. The speed assembly determines the speed of the vehicle with respect to the track and may also be referred to as a speed determiner. The speed determiner **70** is connected to a rail wheel **78** contacting the track **10**.

[0071] With reference to FIGURES 6-8, the sensor **74** includes a magnet **80** and a pick-up coil **82**, which acts as a sensor. As teeth **84** along the toothed gear **72** pass by the sensor **74**, a back electromagnetic force (voltage) is induced into the pick-up coil **82**. The frequency of the voltage is proportional to the speed of the vehicle. The variable alternating current ("A.C.") voltage is transmitted, for example, from the magnet **80** and coil **82** to a frequency-to-voltage converter **88** (see FIGURE 8). The frequency-to-voltage converter **88** produces a direct current ("D.C.") voltage proportional to the speed of the vehicle **28** traveling on the track **10**. The D.C. voltage is transmitted to an analog-to-digital converter **90**, which transforms the analog signals into a digital format. The digital signals are then transmitted to the computing device **42** for processing.

[0072] With reference to FIGURES 9, a distance measurement assembly **91** serves as a distance determiner (e.g., an odometer). The distance measurement assembly **91** includes first and second light sources **100, 102**, respectively, and first and second light detectors **104, 106** (e.g., phototransistors), respectively, positioned near slots **110** in first and second plates **112, 114**, respectively, along an axis **92** including the wheel **78**. The distance determiner of the distance measurement assembly **91** acts to measure relative incremental distance (as opposed to "absolute" distance) that the vehicle **28** travels. The plates **112, 114** are preferably positioned such that a slot **110** in the first plate **112** "leads" a slot **110** in the second plate **114** by some portion of degrees (e.g., about 90 degrees), thereby forming a quadrature encoder. Hence, the distance measurement assembly being described may also be referred to as a quadrature encoder assembly.

[0073] With reference to FIGURES 9 and 10, electrical pulses represented by phase A **116** and phase B **118** are received by the detectors **104, 106** when light from the sources **100, 102** passes through the slots **110** in the respective plates **112, 114**. The space between each of the slots **110** is known. Furthermore, each of the plates **112, 114** rotates as a function of the distance the vehicle travels. As indicated by the dotted lines in FIGURE 10, the pulses **116, 118** are out-of-phase by some portion of degrees (e.g., about 90 degrees). Both phase A **116** and phase B **118** are transmitted from the detectors **104, 106** to the computing device **42**, which determines the distance the vehicle **28** has moved as a function of the number of pulses produced by one of the phase. Also, the direction in which the vehicle **28** is moving is determined by whether the phase A **116** of the first plate **112** leads or lags phase B **118** of the second plate **114**.

[0074] The distance is preferably determined in one of two ways. The distance determiner of the distance measurement assembly **91** requires the vehicle **28** to start at, and proceed from, a known location. For example, the vehicle **28** may proceed between two (2) "mile-posts." Alternatively, a differentially corrected global positioning system ("DGPS") **222** may be used to avoid manually identifying location information. This alternative is necessary where manual intervention is not available. More specifically, the position of the vehicle **28** is obtained from the GPS **222**. Then, the distance determiner of the distance measurement assembly **91** is used to update

the position of the vehicle **28** between the GPS transmissions (e.g., if the vehicle is in a tunnel).

[0075] With reference to FIGURES 8, 9, and 10, the speed may also be determined from either phase **116** or **118** of the distance measurement assembly **91**. The electrical pulse **116, 118** from each detector **104, 106** provides a pulsed signal with a frequency of the pulse proportional to the vehicle speed. Accordingly, the distance measurement assembly **91** may be used in place of the speed determiner **70** of FIGURE 6. For example, the phase A **116** may be fed to the frequency-to-voltage converter **88** from detector **104** with the circuit of FIGURE 6 operating in the same manner as described above. Either method of determining speed in combination with train control speed information will yield a true vehicle speed (i.e., true "ground speed") with respect to the rail bed.

[0076] With reference to FIGURES 19 and 20, the drawbar force assembly **220** includes strain gauges **244** mounted on a drawbar **246** of the vehicle **28** (e.g., a lead unit **252**). These strain gauges are mounted such that the voltage output is an analog signal proportional to longitudinal tension of the train on the drawbar. The analog signal is transmitted to the respective analog-to-digital converter (e.g., **38**), which transforms the analog signal into a digital format, then to the computing device **42** (see FIGURE 15). The longitudinal tension is processed as a feed-forward into the locomotive train control model.

[0077] Referring to FIGURES 14 and 21, the communications device **216** may utilize any suitable communications technology to communicate with locomotive control computers **250** in lead units **252** associated with the vehicle **28** and a centralized control office **260**. While typically the lead units **252** communicate with locomotive control computers **254** in helper units **256** operating in the middle of the train, the communications device may also utilize any suitable communications technology to communicate locomotive control computers **254** in helper units **256**. Similarly, the communications device **216** may also utilize any suitable communications technology to communicate with the truck lubrication system **274** in the vehicle **28** and, if the vehicle is associated with a train, truck lubrication systems in other vehicles associated with the train. Likewise, the communications device **216** may also utilize any suitable communications technology to communicate with the

truck steering mechanism **276** in the vehicle **28** and, if the vehicle is associated with a train, truck steering mechanisms in other vehicles associated with the train. For example, the communications device **216** may utilize cable connections and a standard electrical communications protocol (i.e., Ethernet) to communicate, for example, with locomotive control computers in the lead units **252**. Additionally, the communications device **216** may utilize wireless communications (e.g., radio frequency (RF), infrared (IR), etc.) to communicate, for example, with locomotive control computers in the lead units **252** or helper units **256**.

[0078] The communications device **216** may utilize other wireless communications (e.g., cellular telephone, satellite communications, RF, etc.) to communicate, for example, with the centralized control office. For example, a cellular modem is optionally used in the vehicle **28** to automatically update a data bank of known track defects at the centralized control office. More specifically, as the vehicle travels on the track in a geographic area (e.g., North America), the analyzer **140, 200** collects and analyzes information. When a track defect is detected, the information is transmitted (uploaded) to a main computer at the centralized control office via the cellular modem. The cellular modem is also optionally used in the analyzer **140, 200** to collect or receive train manifest information. The train manifest information includes the sequence of locomotives and railroad cars and physical characteristics about each vehicle in the train. This information is stored in a look-up table **226** and used by software applications in the computing device **42** (e.g., dynamic modeling software).

[0079] Additionally, the communications device (e.g., cellular modem) is optionally used in the analyzer **140, 200** to communicate with upcoming track features such as switches and crossings. In combination with a GPS **222**, the computing device **42** knows the current position of the vehicle **28**. Therefore, the computing device **42** also knows of upcoming track features. The analyzer **140, 200** may, for example, communicate with a switch to verify that the switch is currently aligned for travel by the vehicle or associated train. The analyzer **140, 200** could also communicate with an upcoming "intelligent" crossing to determine whether or not there is an obstacle on the track.

[0080] With reference to FIGURES 5 and 11, a degree-of-curve is defined as an angle **α** subtended by a chord **120** (e.g., 100 foot). The distance determiner discussed above is used in the calculation of the chord **120** distance. Also, the rate gyro and speed determiner discussed above are used to determine the degree-of-curve. More specifically, the rate gyro **50, 204** (see FIGURE 4) and the speed determiner **70, 91** (see FIGURES 6 and 9) may determine a certain rate in degrees/foot. That rate is then multiplied by the length of the chord **120** (e.g., 100 feet), which results in the degree-of-curve. The degree-of-curve represents a "severity" of a particular curve in the track **10**.

[0081] FIGURE 12 represents a graph **121** of degree-of-curvature versus distance. As a vehicle enters/exits a curve in a track (see, for example, FIGURE 5), the degree-of-curvature changes. While the vehicle is on straight track (e.g., a tangent) or in the body of a curve having a constant radius, the degree-of-curvature remains constant **122, 123**, respectively. A point **124** represents a beginning of an entry spiral; a point **125** represents an end of the entry spiral/beginning of a body of curve; a point **126** represents an end of the body of curve/beginning of an exit spiral; and a point **127** represents an end of the exit spiral. The entry and exit spirals represent transition points between straight track and the body of a curve, respectively. Determining whether the vehicle is on a straight track (tangent), a spiral, or a curve is important for determining what calculations will be performed below.

[0082] Data representing engineering standards for taking corrective actions may be pre-loaded into a look-up table **226** (e.g., a storage or memory device) included in the computer system **218**. The following corrective actions, for example, may be identified:

1) Safety Tolerances that, when exceeded, identify Urgent defects (UD1) that must be attended to substantially immediately;
2) Maintenance Tolerances that, when exceeded, identify Priority defects (PD1) that may be attended to at a later maintenance servicing;
3) Curve Elevation Tolerances (CET) that, when exceeded, identify potentially unsafe curve elevations; and

4) Maximum Allowance Runoff (MAR) Tolerances that, when exceeded, identify potentially unsafe uniform rise/falls in both rails over a given distance.

[0083] The defects discussed above are typically classified into at least two (2) categories (e.g., Priority or Urgent). Priority defects identify when corrective actions may be implemented on a planned basis (e.g., during a scheduled maintenance servicing or within a predetermined response window). Urgent defects identify when corrective actions must be taken substantially immediately. The classification of defects will also yield actions to be taken to influence the control and operations of the vehicle or associated train. The classifications of defects and identification of control actions are performed in real-time.

[0084] It is to be understood that it is also contemplated to store other parameters relating to the vehicle and/or track in the look-up table **226** in alternate embodiments.

[0085] As discussed above, tangents are identified as straight track. Curves correspond to a body of a curve, i.e., the constant radius portion of a curve. Warp-in-tangents and curves (i.e., Warp 62) are calculated as a maximum difference in cross-level (i.e., superelevation) anywhere along a "window" of track (e.g., 62' of track) while in a tangent section or a curve section. This calculation is made as the vehicle moves along the track. This calculated parameter is then compared to the data (e.g., engineering tables) discussed above, which is preferably stored in the look-up tables. A determination is made as to whether the current section of the track is within specification. If the section of track is identified as not being within specification, a message is produced and the offending data is noted in an exception file, appears on a readout screen of the video display device **142**, and is passed along to the train control computers **250**, **254** and the centralized control office **260** via the communications device **216**.

[0086] Warp in spirals (i.e., Warp 31) are calculated as a difference in cross-level (i.e., superelevation) between any two points along a length of track (e.g., 31' of track) in a spiral. The data is also calculated as the car moves along the track. This calculated parameter is compared to the data stored in the look-up tables for determining whether the section of track under inspection is within specification. If the section of track is identified as not being within specification, a message is

produced and the offending data is noted in the exception file, appears on a readout screen of the video display device **142**, and is passed along to the train control computers **250**, **254** and the centralized control office **260** via the communications device **216**.

[0087] A calculation is also made for determining cross-level (i.e., superelevation) alignment from design parameters at a particular speed. More specifically, this calculation determines a deviation from a specified design alignment. If an alignment deviation is found, it is noted in the exception file and the system calculates a new recommended speed, which would put the track back within design specifications.

[0088] A rate of runoff in spirals calculation, which determines a change in grade or rate of runoff associated with the entry and exit spirals of curves, is also performed. The rate of runoff in spirals calculation is performed over a running section of track (e.g., 10') and is compared to design data at a given speed for that section of track. If the rate of runoff is found to exceed design specifications, the fault is noted in the exception file, and a new, slower speed is calculated for the given condition.

[0089] Also, a frost heave or hole detector is optionally calculated. The frost heave or hole detector looks for holes (e.g., dips) and/or humps in the track. The holes and humps are longer wavelength features associated with frost heave conditions and/or sinking ballasts.

[0090] The analyzer **140**, **200** also performs a calculation for detecting a harmonic roll. Harmonic rolls cause a rail car to oscillate side to side. A harmonic roll, known as rock-and-roll, can be associated with the replacement of a jointed rail with continuously welded rails ("CWR") for a ballast which previously had a jointed rail. The ballast retains a "memory" of where the joints had been and, therefore, has a tendency to sink at that location. This calculation for detecting harmonic rolls identifies periodic side oscillations associated in a particular section of track.

[0091] All the raw data described above is logged to a file. All spirals and curves are logged to a separate file. All out-of-specification particulars are logged to a separate file. All system operations or exceptions are also logged to a separate date file. All the raw data described above is detected in real-time as the vehicle **28** travels on the track **10**. The analysis of parameters based on the raw data with respect to acceptable tolerances stored in the look-up table **226** is also performed in real-time.

[0092] "Real-time" refers to a computer system that updates information at substantially the same rate as it receives data, enabling it to direct or control a process such as vehicle control. "Real-time" also refers to a type of system where system correctness depends not only on outputs, but the timeliness of those outputs. Failure to meet one or more deadlines can result in system failure. "Hard real-time service" refers to performance guarantees in a real-time system in which missing even one deadline results in system failure. "Soft real-time service" refers to performance guarantees in a real-time system in which failure to meet deadlines results in performance degradation but not necessarily system failure.

[0093] The analyzers **140, 200** of the invention detect track and vehicle parameters in real-time and determine if the parameters are within acceptable tolerances in real-time. The analyzers **140, 200** may also provide information to the video display device **142** in real-time indicating the results of such analyses and recommended actions. Likewise, the analyzers **140, 200** may also provide information to the locomotive control computers **250, 254** indicating the analysis results and recommended actions in real-time. Thus, the information may be available in real-time to operators (e.g., engineers) within view of the video display device **142** and for further processing by the locomotive control computers **250, 254**. Such real-time performance by the analyzers **140, 200** is within one second of when the appropriate track and vehicle characteristics are presented to the associated detectors. From a performance view, "hard real-time service" is preferred, but "soft real-time service" is acceptable. Therefore, "soft real-time service" is preferred where cost constraints prevail, otherwise "hard real-time service" is preferred.

[0094] All of the data is preferably available for substantially real-time viewing (see video display device (e.g., computer monitor) **142** in FIGURES 14 and 21) in the vehicle **28**. Depending on the real-time performance, dimensions/resolution of the display, and screen design, the substantially real-time information appearing on the monitor typically reflects track/vehicle conditions between approximately 100' and approximately 6,000' behind the vehicle when the vehicle is traveling at approximately 65 MPH.

[0095] FIGURE 13 illustrates a cross-level (i.e., superelevation) **128** for a track **10**. Cross-level for tangent (straight) track is typically about zero (0). Allowable

deviations of the cross-level are obtained from the data describing Safety Tolerances in the look-up table **226**.

[0096] The variations in the cross-level (i.e., superelevation) are related to speed. The designation is the "legal speed" for a section of track. This designation is defined in another set of tables, which relate speed to actual track position (mileage). Therefore, the system is able to determine the distance (mileage) and, therefore, looks-up the legal track speed for that specific point of track. The system is able to determine whether the vehicle is on tangent (straight) track, curved track, or spiral track as in the graph shown in FIGURE 12. An example of calculations for tangent (straight) track is discussed below.

[0097] To determine whether the vehicle is on tangent (straight) track, curved track, or spiral track, the system takes a snap-shot of all the parameters at one foot intervals, as triggered by the distance determiner. Therefore, the system performs such calculations every foot. The data are then statistically manipulated to improve the signal-to-noise ratio and eliminate signal aberrations caused by physical bumping or mechanical "noise." Furthermore, the data are optionally converted to engineering units.

[0098] More specifically, at a given time (or distance), if the vehicle is on a tangent (straight) track and traveling 40 mph with an actual cross elevation (i.e., superelevation) of 1-1/8", the system first determines an allowable deviation, as a function of the speed at which the vehicle is moving, from the look-up table including data for Urgent defects (UD1). For example, the allowable deviation may be 1-1/2" at 40 mph. Since the actual cross elevation is 1-1/8" and, therefore, less than 1-1/2", the cross elevation is deemed to be within limits.

[0099] The system then looks-up a 1-1/8" cross elevation (i.e., superelevation) in the Priority defects table (PD1) as a function of the speed of the vehicle (e.g., 40 mph) and determines, for example, that an acceptable tolerance of 1" for cross elevation exists at 40 mph. Because the actual cross elevation (e.g., 1-1/8") is greater than the tolerance (e.g., 1"), the system records a Priority defect for cross elevation from design.

[00100] If, on the other hand, the actual cross elevation (i.e., superelevation) is 1-5/8", the system would first look-up the Urgent defects table (UD1) at 40 mph to

find, for example, that the allowable deviation is 1-1/2". In this case, since the actual cross elevation is greater than the allowable cross elevation, the system would record an "Urgent defect" of cross elevation from design. Because the priority standards are more relaxed than the urgent standards, the system would not proceed to the step of looking-up a Priority defect.

[00101] Since an Urgent defect was discovered, the system would then scan the Urgent defects look-up table UD1 until a cross-level (i.e., superelevation) deviation greater than the current cross elevation (i.e., superelevation) is found. For example, the system may find that a speed of 30 mph would cause the Urgent defect to be eliminated. Therefore, the system may issue a "slow order to 30 mph" to alert the operator of the vehicle to slow the vehicle down to 30 mph (from 40 mph, which may be the legal speed) to eliminate the Urgent defect. If the deviation of the actual cross elevation from the tolerance is great (e.g., greater than 2-1/2"), the a repair immediately condition will be identified.

[00102] From the rate gyro-speed determiner condition, the computing device determines when the vehicle is in a body of a curve. Therefore, when the vehicle is in the body of a curve, the system looks up the curve elevation for the legal speed from the curve elevation table. The system then looks up the allowable deviation from the Urgent defects look-up table UD1 and determines the current cross elevation (i.e., superelevation) is less than or equal to: design cross elevation ± allowable deviation for the cross elevation. If that condition is satisfied, the computing device determines that curve elevation is within tolerance. If that condition is not satisfied, the allowable deviation table is searched to find a vehicle speed that will bring the curve elevation table into tolerance. If such a value cannot be found, a repair immediately (e.g., Urgent defect) condition is identified.

[00103] The track/vehicle analyzer **200** also utilizes the current cross-level (i.e., superelevation) and curvature to determine a "balanced" speed (as described in the Background above) for the vehicle 28. The "balanced" speed is also known as the "equivalent" speed. This is the ideal speed of travel around a curve, given the current curvature and cross-level of the curve in question.

[00104] The analyzer **140, 200** described above are used as a real-time track inspection device. The analyzers may be utilized by track inspectors as part of his/her

regular track inspection such that the analyzer points out any track geometry abnormalities and recommends a course of action (e.g., immediately repair the track or slow down the vehicles and trains on a specific section of the track). The analyzer accomplishes this task by comparing physical parameters of the track with the original design parameters combined with the allowed variances for that particular speed. These parameters are stored in design look-up tables **226** (e.g., storage or memory devices) within the computer system **218**. If the analyzer identifies a particular section of track that is out of specification, the analyzer identifies a speed that the car may safely travel on that track section.

[00105] The device disclosed in the present invention may be mounted in a lead unit **252**. As the lead unit travels along the track, the analyzer **140, 200** takes continuous readings. For example, the analyzer measures the rail parameters, collects position information of the lead unit (i.e., vehicle) on the track, determines out-of-specification rails of the track, and/or stores the particulars of that track defect in a storage or memory device, preferably included within the computer system. The analyzer then optionally communicates the information to the centralized control office **260** via the communication device **216**. More specifically, for example, the communication device detects an active cellular area, automatically places a cellular telephone call, and dumps (downloads) the track defect data into a central computer at the centralized control office.

[00106] The analyzer **140, 200** also notifies a vehicle operator (e.g., train engineer) that the vehicle has passed over an out-of-specification track via the video display device **142**. Furthermore, the analyzer notifies the engineer to slow down the train to remain within safety limits and/or to take other corrective measures as seen fit to resolve the problem.

[00107] In an alternate embodiment, it is contemplated to implement the device as a "Black Box" to record track conditions. Then, in the event of a derailment, the data could be used to identify the cause of the derailment. In this embodiment, the system would start, run, and shut-down with minimal human intervention.

[00108] The analyzer **140, 200** preferably includes an instrument box and a computer system **218**. The instrument box is preferably mounted to a frame that accurately represents physical track characteristics. In this manner, the instrument

box is subjected to an accurate representation of track movement. In one embodiment, the frame is a lead unit (i.e., locomotive). However, it is also contemplated that the frame be a railroad car or a track inspection truck.

[00109] The instrument box senses (picks-up) the geometry information and converts it so that it is suitable for processing by the computing device **42**. The track inspection vehicle is also equipped with both a speed determiner and a distance determiner. In the track inspection vehicle configuration, the computing device is mounted in a convenient place. The driver of the vehicle is easily able to view the video display device **142** (e.g., computer monitor) when optionally notified by a "beeping" noise or, alternatively, a voice generated by the computing device. The instrument box can be mounted to the frame assembly of a lead unit. If so, the computer system **218** is placed in a clean, convenient location.

[00110] The instrument box preferably includes the vertical gyro assembly **20, 202** described above. The vertical gyro assembly is used for both cross-level (i.e., superelevation) and grade measurements. The instrument box also includes a rate gyro assembly **50, 204**, which, as described above, is used for detecting spirals and curves. The instrument box also includes an accelerometer assembly **208** with a set of orthogonal accelerometers. The instrument box also includes a temperature sensing assembly **210**. A precision reference power supply and signal conditioning equipment are also preferably included in the instrument box.

[00111] Also, the computer system **218** preferably includes a data acquisition board, quadrature encoder board, computing device **42**, gyroscope power supplies, signal conditioning power supplies, and/or signal conditioning electronics. If the frame is an autonomous locomotive, additional equipment for a digital GPS system **222** and a communications device **216** are also included.

[00112] FIGURE 14 illustrates the track analyzer **140** for analyzing the track according to one embodiment of the invention. The track analyzer **140** includes the computer system **218**, for receiving, storing, and processing data for inspecting rail track. The computer system **218** communicates with the vertical gyro assembly **20, 202** for receiving grade and cross information. The rate gyro assembly **50, 204** supplies the computer system **218** with rate information. The speed assembly **70** supplies the computer system **218** with vehicle speed. The mileage determiner

(odometer) of the distance measurement assembly **91** supplies the computer system **218** with mileage data. The non-contact gauge measurement assembly **206** supplies the computer system **218** with the current gauge of the track (i.e., width between the rails at a point 5/8 of an inch below the head **234** of the rail **130**) The orthogonal accelerometers **238, 240, 242** supply the computer system **218** with the current, instantaneous acceleration in three directions. The temperature sensing assembly **210** supplies the computing device with the current temperature of the system components such that corrections to the raw data may be initiated to correct for any temperature dependant drift. The computer system **218** processes the data received from the various components to determine the various conditions of the track discussed above. A video display device **142** displays the messages regarding the out of tolerance defects.

[00113] With reference to FIGURES 1, 14, and 21, it is to be understood that the analyzer **140, 200** is mounted within the vehicle **28**.

[00114] In one aspect, the analyzers **140, 200** improve the operational safety and overall efficiency, including fuel efficiency, vehicle wheel wear, and track wear, for a track and an individual vehicle or a train traveling on the track through communications with locomotive control computers **254** in a lead unit (i.e., locomotive) **252** associated with the vehicle **28**. The analyzer determines a plurality of track and vehicle parameters as described above. In addition, the analyzer further calculates the balance speed for the current track geometry and compares the current vehicle speed to the calculated balance speed to determine if the current vehicle speed is within acceptable tolerances of the balance speed. The current technology in locomotive traction control is based on an average North American curve of approximately 2.5 degrees. If real-time rail geometry data, including current curvature and cross-level (i.e., superelevation), can be provided, then the drive system can be optimized for current track conditions, resulting in maximum efficiency. The relationship between the tractive force that drives the locomotive, or other type of vehicle, forward on a rail is expressed by the following equation:

$$F_{Traction} = F_{Normal} * u$$

where u is the coefficient of static friction and F_{Normal} is the normal force at the rail / wheel interface.

[00115] Balance speed is the optimum speed of the vehicle at which the resultant force vector is normal to the rail. By maintaining a vehicle at its balanced speed point, F_{Normal} is maximized. Accordingly, $F_{Traction}$ is also maximized when the vehicle is operated at its balanced speed. Furthermore, by maintaining the drive wheels at the highest point of static friction while operating at the balanced speed, the maximum amount of available tractive force ($F_{Traction}$) is achieved. A small change in the velocity (V) through a curve results in significant changes in the lateral (centripetal) forces, as shown in the following equation:

$$F_{Lateral} = Mass * A_{lateral},$$

$$\text{where } A_{lateral} = (1/ R_{curve}) * V\hat{}\,2$$

[00116] Geometrical information about the rail and vehicle is necessary to compute the vectorial sum of the lateral force and the gravitational force in order to ultimately compute the balance speed for the most efficient operation of the vehicle, train, and track. Lateral contact forces between a rail wheel flange of the vehicle and the rail on which the vehicle is traveling gives rise to frictional forces that decelerate the vehicle and reduce the efficiency of the drive system. To overcome these frictional forces requires additional energy beyond the traction forces that are required to drive the rail vehicle forward at the lowest possible energy. The traction force, which is normal to the rail / wheel interface is enhanced by the locomotive drive wheels being spun at a rotational velocity slightly higher than the forward velocity requires. If the current vehicle speed is not within acceptable tolerances of the balance speed, the analyzer provides the necessary track information (e.g., track, vehicle, and balance speed parameters) and an optimized control strategy to the locomotive control computer **250**. The optimized control strategy maximizes fuel efficiency and safety and minimizes premature rail wear and premature vehicle wheel wear.

[00117] The locomotive control computer **250** takes in the data from the track analyzer and computes the required alterations to the current control strategy toward the end of improving safety and efficiency. The locomotive control computer can then provide engine performance parameters and further information regarding its fuel consumption back to the track analyzer as feedback. The track analyzer compares the engine performance parameters and additional feedback to the track, vehicle, and balance speed parameters and the optimized control strategy and attempts to further

optimize the control strategy. This feedback control mechanism can be implemented in various degrees of complexity (e.g., iterated multiple times or continuously).

[00118] In another aspect, the analyzers **140, 200** can improve the operational safety and overall efficiency, including fuel efficiency, vehicle wheel wear, and track wear, for a track and a train traveling on the track through communications with locomotive control computers **254** in helper units **256** of train. The analyzer determines a plurality of track and vehicle parameters (e.g., forces on a drawbar of the vehicle) as described above. The track analyzer provides the necessary track information (i.e., track and vehicle parameters) to the locomotive control computers **254** of other vehicles (e.g., helper units **256**) such that overall train performance is enhanced. For example, forces on the drawbar of the vehicle are optimized. This is accomplished with drawbar force information from the drawbar force assembly **220**, along with other geometry information from other detectors and instruments.

[00119] In still another aspect, the analyzers **140, 200** can improve the operational safety and overall efficiency, including fuel efficiency, vehicle wheel wear, and track wear, for a track and an individual vehicle or a train traveling on the track through communications with truck lubrication systems **274** in the individual vehicle or one or more vehicles associated with the train. The analyzer determines a plurality of track and vehicle parameters as described above. The track analyzer processes the necessary track information (i.e., track and vehicle parameters) in the geometry system process **266** and vehicle optimizer process **268** to determine the optimized lubrication strategy and communicates the optimized lubrication strategy to the truck lubrication system(s) **274** such that overall train performance is enhanced. For example, vehicle wheel wear is optimized.

[00120] In yet another aspect, the analyzers **140, 200** can improve the operational safety and overall efficiency, including fuel efficiency, vehicle wheel wear, and track wear, for a track and an individual vehicle or a train traveling on the track through communications with truck steering mechanisms **276** in the individual vehicle or one or more vehicles associated with the train. The analyzer determines a plurality of track and vehicle parameters as described above. The track analyzer processes the necessary track information (i.e., track and vehicle parameters) in the geometry system process **266** and vehicle optimizer process **268** to determine the optimized

steering strategy and communicates the optimized steering strategy to the truck steering mechanism(s) **276** such that overall train performance is enhanced. For example, fuel efficiency, vehicle wheel wear, and track wear are optimized.

[00121] In still another aspect, the analyzers **140, 200** can improve the operational safety for a track and autonomous vehicles and trains traveling on the track through communications with a centralized control office **260**. The analyzer determines a plurality of track and vehicle parameters as described above. When the analyzer has determined a non-compliance geometry condition exists, after the analyzer has taken steps to protect vehicle **28**, the analyzer notifies the centralized control office via the communications device **216** (e.g., cellular data modem).

[00122] The centralized control office **260** determines an appropriate action to be taken (e.g., initiate maintenance of the track defect, issue a slow order to future trains traveling over the same area until maintenance is completed). The slow order is ultimately communicated to analyzers **140, 200** in such trains so that recommended actions by the analyzer are determined in the context of the slow order. Additionally, the centralized control office may append the track defect and associated information from the analyzer to historical records of track defects, related problems, and associated maintenance actions. The centralized control office may then, with discretion, choose to send out maintenance personnel to verify and/or repair the specified track area.

[00123] In yet another aspect, the analyzers **140, 200** can dynamically model a behavior of each vehicle associated with a train or an autonomous vehicle traveling on a track. The analyzer includes a train manifest stored in the look-up table **226**, which includes the train car sequence information. The train manifest is based on initial operation (startup) of the train. The train manifest can be downloaded into the look-up table using the communications device (e.g., cellular data modem) **216**. Alternatively, the train manifest can be copies from removable storage media (e.g., floppy disk, CD-ROM, etc.) to the look-up table. The train manifest may even be entered manually using the keyboard and saved to the look-up table. The look-up table also includes physical car characteristics and a plurality of parameters describing the car handling situations (i.e., operating characteristics) for each vehicle of the train. The analyzer **140, 200** determines a plurality of track and vehicle parameters as

described above. The computer system **218** performs a series of calculations to model each vehicle under current track geometry conditions. The analyzer determines a statistical probability of each vehicle causing a potential derailment situation based on the current conditions and identifies the vehicle with the highest probability. The analyzer determines if the highest probability of derailment exceeds a minimum acceptable probability. If the highest probability of derailment exceeds the minimum acceptable probability, the analyzer determines a recommended course of action to reduce the probability of derailment below the minimum acceptable probability. The track analyzer will notify the vehicle operator of the situation and recommended course of action via the video display device **142**. The analyzer will also communicate the recommended course of action to the locomotive control computer **250** to change the current control strategy to reduce the probability of derailment. Once the high-risk vehicle has traveled beyond the identified risk area, the analyzer will further communicate a message to the locomotive control computer to resume standard train operations.

[00124] In dynamically modeling an autonomous vehicle, the look-up table **226** also includes recent historical geometric conditions of the upcoming track. The computer system **218** performs calculations to model the autonomous vehicle over the upcoming track using the historical track geometry conditions. The analyzer **140, 200** determines a statistical probability of the autonomous vehicle derailing based on the historical geometric conditions of the upcoming track. If necessary, the analyzer determines a recommended course of action to reduce the probability of derailment of the autonomous vehicle to below a minimum acceptable probability.

[00125] While the invention is described herein in conjunction with exemplary embodiments, it is evident that many alternatives, modifications, and variations will be apparent to those skilled in the art. Accordingly, the embodiments of the invention in the preceding description are intended to be illustrative, rather than limiting, of the spirit and scope of the invention. More specifically, it is intended that the invention embrace all alternatives, modifications, and variations of the exemplary embodiments described herein that fall within the spirit and scope of the appended claims or the equivalents thereof.